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THE ROYAL SOCIETY

Predictions of extreme precipitation and sea-level rise under climate change

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Two aspects of global climate change are particularly relevant to river and coastal flooding: changes in extreme precipitation and changes in sea level. In this paper we summarize the relevant findings of the IPCC Third Assessment Report and illustrate some of the common results found by the current generation of coupled atmosphere–ocean general circulation models (AOGCMs), using the Hadley Centre models. Projections of changes in extreme precipitation, sea-level rise and storm surges affecting the UK will be shown from the Hadley Centre regional models and the Proudman Oceanographic Laboratory storm-surge model.

A common finding from AOGCMs is that in a warmer climate the intensity of precipitation will increase due to a more intense hydrological cycle. This leads to reduced return periods (i.e. more frequent occurrences) of extreme precipitation in many locations. The Hadley Centre regional model simulates reduced return periods of extreme precipitation in a number of flood-sensitive areas of the UK. In addition, simulated changes in storminess and a rise in average sea level around the UK lead to reduced return periods of extreme high coastal water events. The confidence in all these results is limited by poor spatial resolution in global coupled models and by uncertainties in the physical processes in both global and regional models, and is specific to the climate change scenario used.

Keywords: extreme precipitation; sea-level rise; global climate change; IPCC

1. Introduction

On physical grounds we expect the enhanced greenhouse effect to lead to a more active hydrological cycle with more precipitation on average (Gregory & Mitchell 1995). Such an increase is commonly found in climate models, although they suggest marked spatial and temporal variability about this average. An increase in mean precipitation, assuming no change in the shape of the frequency distribution, would imply an increased frequency of heavy-precipitation events. However, for physical reasons (e.g. Gregory & Mitchell 1995), the increase in these events could be disproportionate to the change in the mean, with a greater fraction of the total precipitation being delivered by such heavy events (implying a change in the shape of the frequency distribution). Such a shift towards heavy events is a common conclusion of models

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(Cubasch *et al.* 2001). Hence, heavy-precipitation events could also increase in frequency even where mean precipitation decreases. The robustness of global model results is limited, as the spatial resolution of these models is low and we do not have great confidence in the precise results for detailed regions. Regional climate models (RCMs) with considerably higher spatial resolution simulate extreme precipitation events more accurately and can be used to add important local detail to projections.

Typical projections of global average sea-level rise are between 9 and 88 cm by the end of this century (Church *et al.* 2001). However, this is not expected to be the same all over the world. Contemporary climate models do not agree about the geographical pattern of changes, although most suggest changes of up to twice the average in some regions. A higher mean sea level leads to an increased incidence of extreme high water levels. In addition to a rise in mean sea level, changes in the tracks or intensity of storms can affect storm-surges, which are driven by strong winds and low pressures. This shows that the meteorological effect, in some localities, may be comparable in importance with the mean sea-level change.

In this paper we will discuss changes in global and regional precipitation and sea-level rise and storm surges. We illustrate some of the main findings of the IPCC Third Assessment Report (TAR) (Houghton *et al.* 2001) with results from the Hadley Centre models. Changes in precipitation will be shown for the UK and southern Africa from the Hadley Centre regional models and changes in UK storm surges will be projected from the Proudman Oceanographic Laboratory storm-surge model forced by the Hadley Centre regional model.

2. Models and experiments

Two Hadley Centre global coupled ocean–atmosphere general circulation models (AOGCMs) are used: HadCM2 (Johns *et al.* 1997) and HadCM3 (Gordon *et al.* 2000). In addition, regional details are taken from the RCMs HadRM2 (Murphy 1999) and HadRM3H (Murphy *et al.* 2002). Information on storm surges has been derived from a depth–mean storm-surge model (Flather & Smith 1998).

HadCM2 and HadCM3 have been developed at the Met Office's Hadley Centre for Climate Prediction and Research. Both models have an atmospheric resolution of 2.5° in latitude by 3.75° in longitude (approximate grid spacing of 300 km at mid-latitudes) and 19 vertical levels. The atmospheric physics in HadCM2 is described in detail by Johns *et al.* (1997) and for HadCM3 by Pope *et al.* (2000). HadCM2 has the same horizontal resolution in the ocean as in the atmosphere, while HadCM3 has an ocean resolution of 1.25° latitude by 1.25° longitude. Both ocean models have 20 vertical levels. HadCM2 uses flux adjustments to maintain a stable and realistic ses-surface temperature (SST) simulation, while these are not needed in HadCM3.

A number of climate change experiments have been conducted with the global models using observed forcing from 1860 to 1990 followed by different scenarios of increases in greenhouse gases and sulphate aerosols from 1990 to 2100. Those shown here have used a scenario where CO_2 increases at a rate of 1% per year (close to the IPCC scenario IS92A (Kattenberg *et al.* 1996)) with and without sulphate aerosols and the more recent IPCC A2 emissions scenario (Cubasch *et al.* 2001).

The regional climate model (Jones *et al.* 1997; Murphy 1999) has been run over Europe and southern Africa and has a 50 km resolution. At the boundaries the RCM takes driving data from a global model. For HadRM2 the driving model is

HadCM2. For HadRM3H the driving model is a high-resolution atmosphere-only model (1.25° latitude by 1.875° longitude) forced with observed SSTs and sea-ice for present day and with added anomalies in SSTs and sea-ice taken from HadCM3 (Murphy *et al.* 2002) for the future climate. HadRM2 was run for a 30-year control period representing the climate of 1961–1990 and a future climate at the end of the 21st century (2080–2100) where CO_2 is increased gradually and on average is about four times greater than in the control. For a fuller description of the design of this experiment see Huntingford *et al.* (2002). HadRM3H has been run for two 30-year periods, again representing 1961–1990 and the end of the 21st century (2070–2100). The latter gives a prediction of how the climate may evolve under the influence of emissions from the IPCC A2 scenario, where the equivalent CO_2 concentration is around three times greater than in the present-day simulation.

A storm-surge model of the northwest European continental shelf region (Flather & Smith 1998) is forced by tidal forcing and boundary conditions from HadRM2 for the present day and for 2080–2100 (Lowe *et al.* 2001).

3. Changes in extremely heavy precipitation

(*a*) *Global*

The IPCC TAR (Cubasch *et al.* 2001; Giorgi *et al.* 2001) concludes that there is some qualitative agreement between different model projections of changes in extreme precipitation. In particular, a result reconfirmed from earlier reports is that the intensity of precipitation events will increase. In addition, where it has been studied, it is found that the likely increase in extreme heavy-precipitation events will be greater than suggested by changes in the mean alone, implying changes in the frequency distribution. The level of confidence given to these conclusions is reasonably high (IPCC confidence levels of very likely or likely (Houghton *et al.* 2001)). Increases in evaporation and precipitation are expected on physical grounds as the hydrological cycle intensifies in a warmer world. More intense precipitation is consistent with increased storminess in winter and increased convective activity in summer as the stability of the atmosphere is reduced through warming at the surface and increased longwave cooling higher in the atmosphere. A more detailed discussion of these mechanisms is given by Gregory & Mitchell (1995). The regional distribution of simulated changes in the mean precipitation varies considerably between models and projections for particular regions are given lower confidence. The Hadley Centre model HadCM3 illustrates such behaviour with, on average, a near doubling of the most extreme 1% of daily precipitation amounts in the control (calculated using a spatially varying threshold based on extreme levels in the control climate) for the 2080–2100 period (1.95%/1.93% in DJF/JJA of precipitation is above the 1% threshold from the control). Part of these differences is due to a simple increase in the mean values, but they also result from more complex changes in the distributions themselves. The patterns of response show qualitative agreement with changes in extreme daily precipitation in other models (see, for example, Hennessy *et al.* 1997; Kharin & Zwiers 2000).

In the fields of hydrology and civil engineering, a common means of examining extreme rainfall is in terms of return periods. For example, structures such as bridges and dams are designed to withstand the largest precipitation event typically anticipated within a particular period (e.g. the 1-in-50-year flood event; note that a 1-in-50-year event does not imply an event every 50 years, but is a measure of its probability).

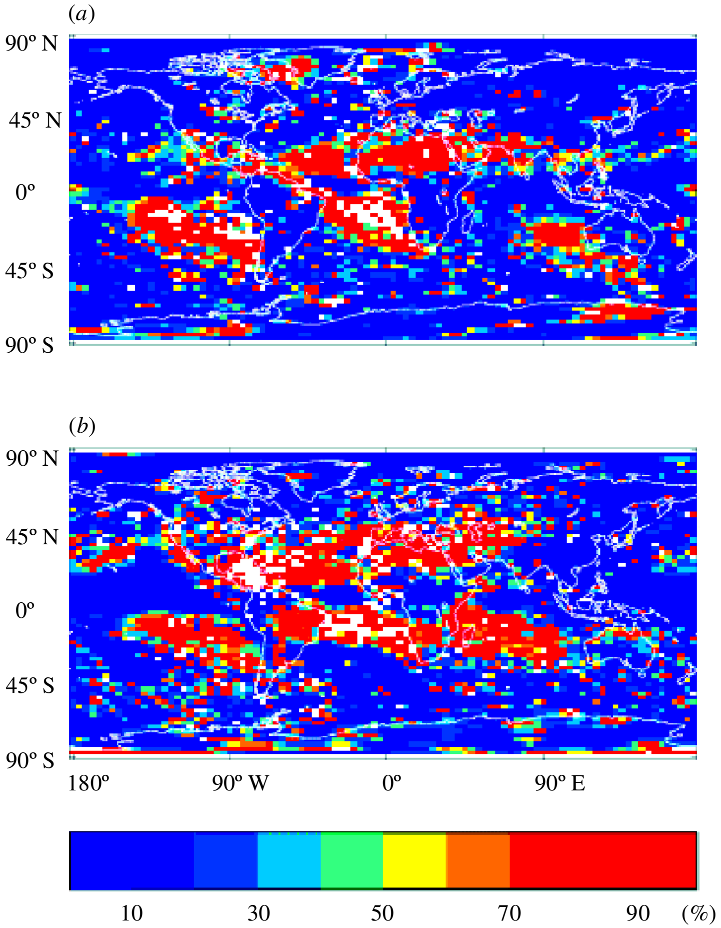

Figure 1. Percentage return period in years of seasonal maximum daily precipitation in the anomaly climate computed for the control 50-year return value. Boxes where the extrapolation has returned inappropriate return values (usually exceptionally high) are not coloured. (*a*) DJF; (*b*) JJA.

We examine this aspect of extreme rainfall events by fitting the three-parameter generalized extreme value (GEV) distribution to values of annual maximum daily precipitation in the HadCM2 model following Zwiers & Kharin (1998) and Kharin & Zwiers (2000) (see Appendix A). The return values for a 50-year return period were computed from control maxima, and the return periods corresponding to these values in the 2080–2100 period were calculated at each grid box. These return periods are shown for DJF and JJA in figure 1. Areas where the return period is greater than 50 years imply that the control extreme event becomes less likely in the future climate. Regionally, there are increases in return period in the subtropics, especially over the Caribbean, northern Africa, the Middle East and the South Atlantic in both seasons, and southern Africa and the Amazonian region of Brazil in JJA. However, the return period reduces substantially everywhere else.

(*b*) *Regional*

While global models can give useful information about changes in physical mechanisms that might lead to changes in the distributions of climate variables such as precipitation, the resolution of typical AOGCMs is too coarse to simulate extremes accurately. Hence, for more accurate projections of changes in extremes we need to use higher resolution. The Hadley Centre RCM nested within the global model has been shown to substantially improve the simulation of extreme precipitation compared with the driving AOGCM (Durman *et al.* 2001) and is used here to give regional detail to future projections.

(*c*) *UK*

Durman *et al.* (2001) show improvements in the simulation of extremely heavy precipitation over the UK in HadRM2 compared with HadCM2. However, flooding is often relatively localized and so it is necessary to evaluate the RCMs' ability to simulate extreme precipitation over small catchments. Huntingford *et al.* (2002) have compared data from a single RCM grid box with areally averaged rain-gauge observations available for 1961–1990 for the river catchment areas of the towns of Lewes, Shrewsbury and York, which all suffered flooding in autumn 2000. For each of these areas the 30 annual maximum (AM) rainfall events were calculated for the rain-gauge data and the RCM simulation for rainfall accumulated over 1, 7, 15 and 30 days. GEV functions were then fitted to the values in the AM series. Figure 2 shows the relation between 15-day AM rainfall and return period. The regional model shows considerable skill in the simulation of the AM, and the analysis of Huntingford *et al.* (2002) indicates that there is no significant difference between the distributions. This good agreement between observations and the RCM simulation of recent climate is a significantly sterner test of the RCM than has been applied in previous work (see, for example, Durman *et al.* 2001).

This good simulation of present-day climate gave Huntingford *et al.* (2002) confidence to compare the simulated extreme value distributions for the recent past and the 2090s (figure 2). The GEV for the latter was estimated from the 20 15-day AM from the RCM simulation for 2080–2100. In this case Huntingford *et al.* (2002) show that the future return periods are significantly reduced. Under this scenario, extreme rainfall events over 15-day durations are projected to become increasingly common with 1-in-40-year events becoming more like 1-in-4-year events by the 2090s.

The confidence in these results as a prediction of future changes is low, as the result is likely to be model and scenario specific. However, the consensus emerging from many GCMs and a range of emissions scenarios on future increases in precipitation over high northern latitudes (Giorgi *et al.* 2001) suggests that this may be qualitatively representative of future climate conditions.

(*d*) *Southern Africa*

The Hadley Centre regional model HadRM3H is being developed to run over many other regions to study changes in worldwide extremes. A recent simulation over a southern African domain illustrates the possibility of investigating changes in extreme precipitation in other flood-sensitive parts of the world.

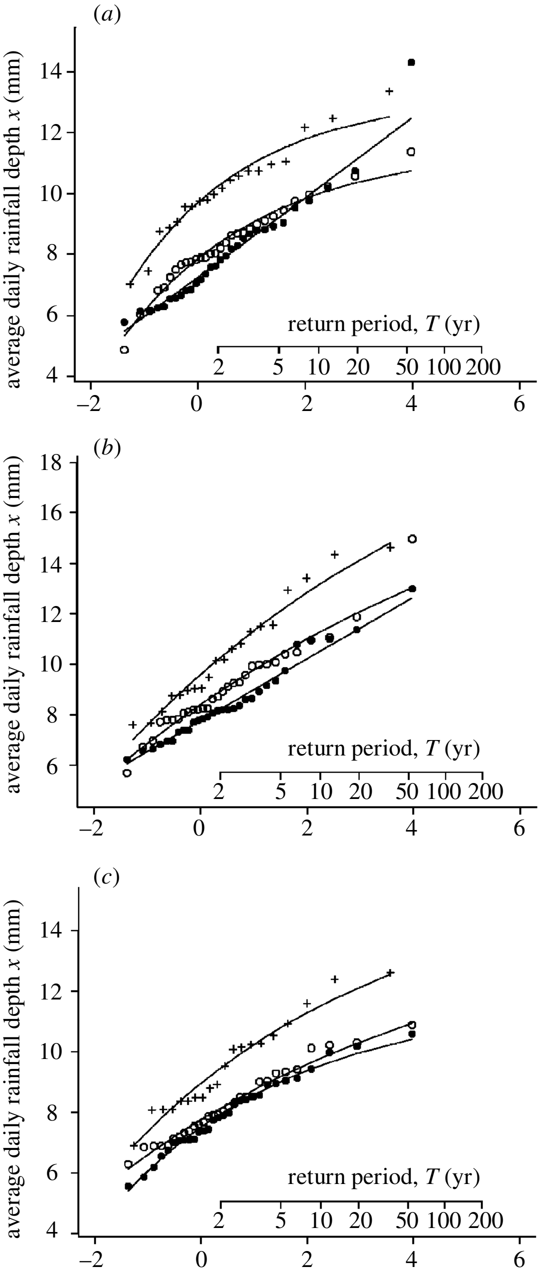

Figure 2. The relation between 15-day-duration annual maximum rainfall and return period. The plots are for the RCM grid squares near to (*a*) Lewes, (*b*) Shrewsbury and (*c*) York. At each site, data are plotted corresponding to measurements for 1961–1990 (filled circles), the RCM simulation representative of recent climate (open circles), and the RCM representative of the climate of 2080–2100 (crosses). The fitted distributions are plotted as smooth curves.

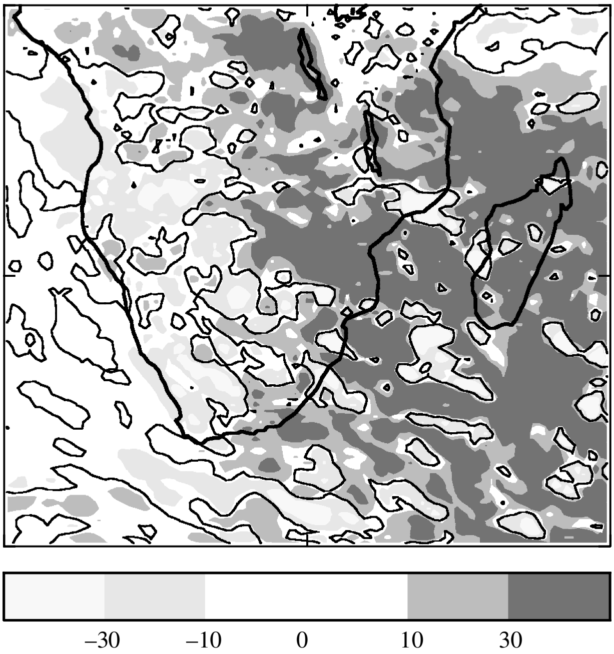

Figure 3. Change in the 20-year rainfall return values (mm d^{-1}) over southern Africa for the 2080s relative to the present day for summer (DJF) for the A2 emission scenario. The zero contour line is shown.

Much of southern Africa experiences a high degree of intra- and interannual rainfall variability, and the region is particularly susceptible to floods and drought. By the 2080s, under the A2 scenario, the regional model predicts a drying over much of the western and subtropical subcontinent, and wetter conditions over eastern equatorial and tropical southern Africa during summer (DJF), when most rain falls. A GEV analysis of summer daily precipitation (figure 3) shows that the amount of rainfall associated with a 1-in-20-year event may become more extreme over large areas of Mozambique, Zimbabwe, Zambia, Tanzania and the Democratic Republic of Congo, typically associated with an increase in the intensity of rainfall rather than more rain days. Less extreme rainfall is predicted over western regions, here associated with a decrease in both the number of rain days and the intensity of rain.

4. Sea-level rise

Changes in extreme sea level can occur as a result of a rise in the mean sea level or through changes in the height of extreme coastal storm-surge events.

(*a*) *Mean sea-level rise*

A rise in mean sea level may increase the risk of flooding by requiring a lower storm-surge height to cause a given high water level. The IPCC TAR (Church *et al.* 2001) projects an increase in global average sea level of between 9 and 88 cm based on a range of AOGCM climate sensitivities and uncertainties in climate-change scenarios. HadCM3 is typical of other models, with a rise between 30 and 50 cm, depending on the scenario used. However, changes in local sea level could be up to twice as much as the global average and depend on fluxes at the ocean surface, transport of heat within the ocean and changes in ocean circulation. Again, such patterns of sea-level rise are model dependent and there is considerable uncertainty amongst GCMs. Another important factor in sea-level rise is the long time-scale effects. The main component of sea-level rise in the medium term, the thermal expansion of the ocean, will continue to occur for many centuries after concentrations of greenhouse gases are stabilized (as the surface warming slowly penetrates the depth of the ocean). Hence, estimates of mean sea-level rise by 2100 will considerably underestimate (by four to nine times (Church *et al.* 2001)) the final equilibrium rise in sea level (which would take many centuries to achieve). In addition, there may be effects in the longer term due to changes in the height of the land and melting of land ice sheets of Greenland and Antarctica.

(*b*) *Extreme events: storm-surges*

The most serious flooding events are often caused by storm-surges, which are temporary increases in sea level above the expected tidal level, caused by reduced atmospheric pressure and the action of strong winds on the water surface. Some AOGCMs have projected increased storm activity which, coupled with increased average sea level, could alter the frequency of storm-surges of a given height.

The impact of such changes on the UK coastline has been investigated by Lowe *et al.* (2001). In their study, the Proudman Oceanographic Laboratory storm-surge model of the northwest continental shelf (Flather & Smith 1998) is driven with winds and pressures from HadRM2 for simulation of the present day and for the end of the 21st century. They find that over much of the model domain there are increases in storm-surge height due to changes in the meteorology that are similar in magnitude to the changes in mean sea level discussed above. The spatial pattern of changes is, however, far from uniform and depends on the local topography and the pattern of changes in meteorology and there is currently little consistency between model projections of storm-surge changes from the few studies performed using driving conditions from different regional models.

An illustration of the combined effects of changes in meteorology and mean sea-level rise on the frequency of extreme water levels at Immingham (a port on the northeast coast of the UK) is given in figure 4. In this extreme example, a present-day 1-in-500-year storm-surge event is projected to occur, on average, once in every 15 years in the future climate when both the increase in mean sea level and the changes in meteorology are included.

5. Summary

The prediction of changes in extreme precipitation and sea level as a result of climate change are uncertain, although some consistent statements are beginning to emerge. Global AOGCMs show some consensus on increased intensity of precipitation in many locations and most models project greater increases in precipitation intensity than are suggested by a simple increase in mean precipitation alone. Most of the

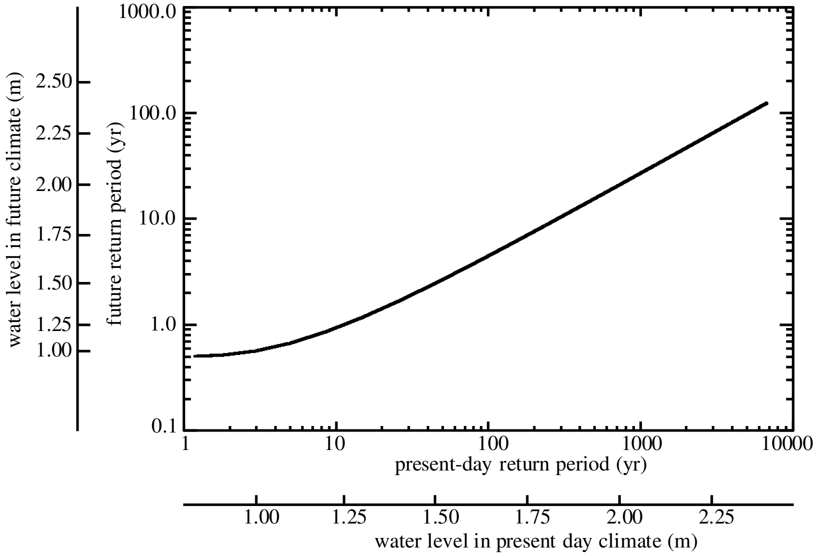

Figure 4. Change in the frequency of extreme water level at Immingham (2080–2100) against the present day, incorporating changes in storminess and a 50 cm rise in mean sea level.

changes predicted by the models are consistent with physical arguments of global changes in the hydrological cycle; however, the resolution of global models means they are unable to accurately capture extreme events and confidence in regional predictions from these models is low.

Regional models show considerably greater skill in capturing extremes, even over small catchment areas. The Hadley Centre regional model HadRM2 has been used to project changes in extreme precipitation and sea-level rise around the UK at the end of the 21st century. The model projects significant reductions in return periods by an order of magnitude for annual maximum rainfall under climate change at several flood-sensitive locations. A rise in mean sea level and increases in storm-surges due to changes in winds and pressure combine to reduce return periods of extreme high water levels at coastal locations around the UK.

Caution must be used in the interpretation of such results. Regional models require driving data from AOGCMs and there are large differences in regional predictions from AOGCMs, arising from differences in climate feedbacks, climate variability and the choice of scenario. In addition, the length of RCM simulations has, to date, tended to be short with consequent problems for studying changes in extremes. Hence, results such as the above are certainly specific to the model used and to the chosen scenario for future climate. If data from such models are used to study the impacts of climate change, such uncertainties must be accounted for.

Appendix A.

The GEV distribution is defined as

$$F(x) = \begin{cases} \exp\{-[1-\kappa(x-\xi)/\alpha]^{1/\kappa}\} & \kappa < 0,\ x < \xi + \alpha/\kappa, \\ \exp\{-[\exp[-(x-\xi)/\alpha]\} & \kappa = 0, \\ \exp\{-[1-\kappa(x-\xi)/\alpha]^{1/\kappa}\} & \kappa > 0,\ x > \xi + \alpha/\kappa, \end{cases}$$

where ξ is the distribution's location parameter, α is the scale parameter and κ describes the distribution shape. These three parameters are found for each grid-box using the method of L-moments (Hosking 1990; Zwiers & Kharin 1998; Kharin & Zwiers 2000). Once the three parameters have been estimated, the return value X_T for a given return period T may be computed,

$$X_T = \begin{cases} \hat{\xi} + \hat{\alpha}\{1 - [-\ln(1 - 1/T)]^{\hat{\kappa}}\}/\hat{\kappa} & \hat{\kappa} \neq 0, \\ \hat{\xi} - \hat{\alpha}\ln[-\ln(1 - 1/T)] & \hat{\kappa} = 0, \end{cases}$$

or, inverting, a return period may be computed for a given return value.

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